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Design of the Locomotion and Docking System of the SwarmItFIX Mobile Fixture Agent

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Abstract

The European project SwarmItFIX has developed a new highly adaptable self-reconfiguring fixturing system which uses a swarm of mobile agents moving freely on a bench and repositioning in real time to better support the machined part. The project investigates the application of robotic multi-agent fixtures for the support of automotive and airplane body panels during their manufacturing and assembly. Each fixturing robot comprises an adjustable end effector, a parallel manipulator, and a mobile-base-docking-bench module. This paper describes the base-bench subsystem which ensures rapid and precise locomotion, as well as secure docking, of the agent during the machining process. The design addresses with particular care the need for a reliable bench-robot coupling and interface as well as the requirement for robustness of the robot's displacements despite the predicaments of the machining environment, such as flying chips, accumulated swarf, spilled fluids, and vibrations. After a brief review of the state of the art, an overview of the whole project is given. Various candidate robot-base designs and locomotion methods are considered and compared. The final design, selected on the basis of the industrial requirements, is described in detail. A prototype of the SwarmItFIX system has been realized within the project and tested on the premises of an Italian aircraft manufacturer.

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Keywords: Mobile robots; reconfigurable fixtures; aeronautics; manufacturing; robotics.

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1. Introduction

Today's smartest adaptable fixtures have limited adjustment capabilities, are mostly operated manually, and are usually set up off-line with the help of external equipment. Significant increase in effectiveness and decrease in cost may come from on-line fully actuated configuration and reconfiguration, large adaptability to different shapes, and the capability to dynamically concentrate the support in the region where manufacturing is actually performed without removing the part from the fixture. The European project SwarmItFIX is based on the novel concept of selfreconfigurable swarm fixtures [1]. Workpiece support is performed by a swarm of mobile robotic agents, each robot able to move autonomously on a bench and reconfigure below the supported part. Combining the flexibility of a mobile robot, the intelligence and reconfigurability of a swarm, and the shape-adaptability of smart materials, the innovative SwarmItFIX fixture system [2], can increase competitiveness, especially in industries with small batch sizes. Indeed, it provides an affordable technology which will reduce inventory, as well as configuration and maintenance time, thus allowing progress towards efficient customer-oriented production. An extensive review of past work on flexible fixtures is given in [3]. More recently, [4] gives an overview of reconfigurable fixturing systems (RFS) and robotic fixtureless assemblies (RFA). The modular RFS in [5] fixes the workpiece by a discrete number of forces. Aoyama and Kakinuma [6] describe a device using a low-melting-temperature alloy to support thin and compliant workpieces. In [7], Arzanpour et al. propose an RFA with suction cup grippers. Munro and Walczyk give a review of pin-type tooling in [8]. An RFS using a parallel manipulator is reported in [9]. Research focusing on novel fixture-design methodologies has also been done: Zhou et al. propose a feature-based approach, using previous design rules and solutions and combining this knowledge with part-geometry information [10]. A FEM-based methodology minimizing machine-force-induced deflection is described in [11]. Despite significant research results and industrial advances towards more efficient fixture systems, important open issues remain. In particular, a system with truly on-line setup and autonomous operation is yet to be achieved. Furthermore, although some solutions available on the market make a valid progress towards this goal, they present bulky and heavy structures that are complex and costly. The SwarmItFIX ideas and results present a clear and concrete improvement of the state of the art.

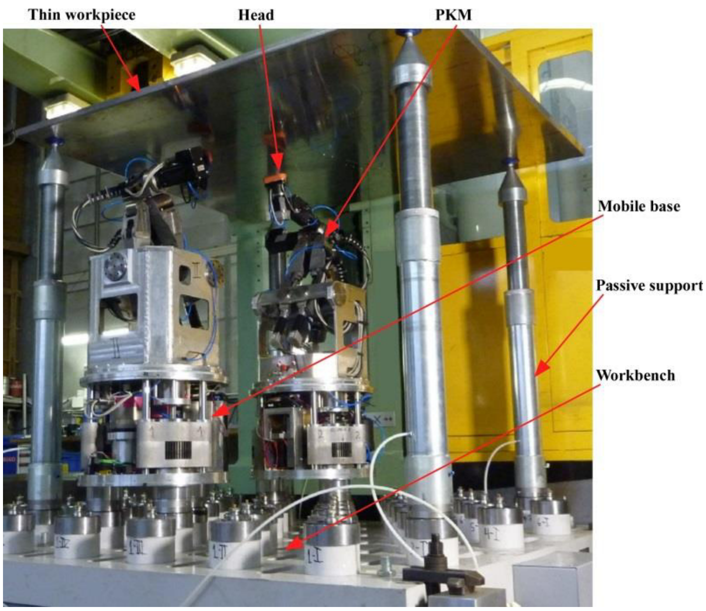


Fig. 1. Complete installation of the SwarmItFIX system prototype, installed in Piaggio Aero Industries.

The new fixture system is more agile, more intelligent, able to operate autonomously, and is capable to adapt to a wider range of parts and operations. The system offers short reconfiguration time, an easy set-up, minimum complexity, and lower costs. To give a clear idea of the SwarmItFIX system, a brief outline is given in Section 2. In the following sections, the paper focuses on the development of one very important sub-module of the system: the mobile base. The latter is responsible for providing fast and precise locomotion to reposition the fixturing agent, as well as the necessary stiffness while docked. Section 3 presents different candidate conceptual designs and locomotion methods for the subsystem. Section 4 compares these possibilities on the basis of industrial requirements, and Section 5 gives a detailed description of the final design of the mobile base and the locomotion system. Section 6 presents the conclusions and results obtained from the installation of the physical prototype of the system installed in Piaggio Aero Industries (Fig. 1), an Italian aircraft manufacturer.

2. Overview of the SwarmItFIX fixture

In commonly used fixture systems the machined piece is supported by mimicking its complete surface, thus providing the required stiffness over its entire surface area. In contrast, to achieve high online adaptability and reconfigurability, in the SwarmItFIX fixture system high-stiffness support is concentrated only in the region near the operating machine tool. The working principle of the system is to make the mobile agents to periodically adjust their position bellow the workpiece following the trajectory of the machine tool and ensuring adequate support only in that local machining region, as detailed in [12]. The SwarmItFIX system is a self-reconfigurable intelligent swarm fixture, composed of mobile agents able to freely move and lock on a purposely designed bench and reposition themselves bellow the supported workpiece [13]. The main target application of the system is the machining of large and thin metal sheets especially important for aircraft manufacturing, but also common in the automotive and other industries. The system is composed of three modules, as shown in Fig. 1:

- An end effector capable of supporting the part by adapting to the local surface geometry [14]
- A parallel manipulator (PM)
- A mobile base and work bench
- Passive supports to hold the work piece in the periphery

2.1. End Effector

The end effector, the supporting head of each mobile agent, ensures shape-adaptability and adhesion to the work-piece. Phase-change magneto-rheological (MR) fluid helps to realize adaptation, while vacuum suction is used for adhesion. The head shape is an equilateral triangle with 80 mm side length. A crown of 27 miniature pins partially submerged in MR fluid, forming a cloud of contact points adapting to the surface, is located at the edge of the triangle. The MR fluid container has a network of channels that allows and blocks the motion of the pins. Inside the end effectors body, a pneumatic cylinder drives a permanent magnet closer to the MR container increasing the magnetic field; this triggers the change of phase and blocks the pistons in position. Complete details are given in [12].

2.2. Parallel manipulator

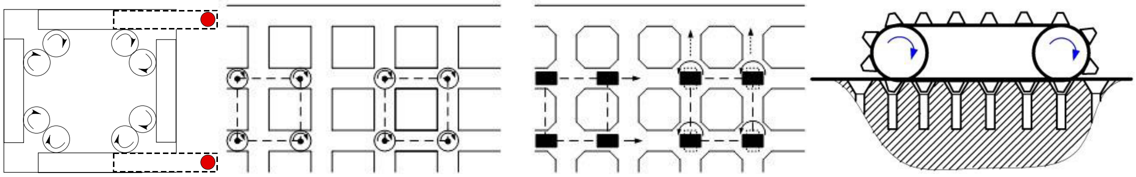
The PM provides support to the end effector and gives fine tuning to the macro position given by the mobile base. It is a 6-DoF hybrid Exechon architecture. Analysis and detailed description of the architecture are given in [15-16]. As a variant to a nominal Exechon PKMs (parallel kinematic machines, i.e., PMs used as machine tools) it has a 3 DoF spherical wrist and is smaller in dimensions.

2.3. Parallel manipulator

The mobile base is the supporting platform of the PM. It has being designed together with the work bench in order to assure a correct and easy interface between the two. In the following sections detailed description of the mobile-base and work-bench design are given as well as the description of the adopted locomotion principle.

3. Mobile base architecture

Taking into account the basic design requirements, alternative locomotion methods were proposed and analyzed. Among several ideas five locomotion principles stood out and were studied: sliding, rolling in grooves, tracks, direct rolling, and swing motion. In the following, a brief explanation will be given of each of them with examples of a possible mechanism using each method. To differentiate the mechanisms studied for each method these will be numbered in sequential order, S1, S2, and so on.



a) b) c)

Fig. 2. Sliding locomotion methods: a)S1 mechanism with rack and pinion transmissions; b) Rolling in grooves locomotion methods S2 and S3; c) Tracks locomotion method S4.

3.1. Sliding

In this scenario, the mobile base can crawl on the bench by pulling itself with sliding arms. The mechanism, S1, analysed for this locomotion method employs four pairs of rack and pinion transmissions, two orthogonal with respect to the remaining two, thus permitting a change in direction of the mobile base, with embedded pins that can be inserted in a grid of holes located in the work bench surface. The initial step is given by the gears driving their corresponding racks and actuating the sliders parallel to the direction of motion. The sliders move forward until the pins located on the extremity are inserted in the bench. Then, the gears rotate backwards pulling the base in a forward motion, see Fig. 2a. An advantage of this solution is the accurate positioning and the safety of the step with no risk of deviation from the trajectory due to accidental external forces.

3.2. Rolling in grooves

The grid of holes located in the bench is replaced by a grid of grooves in which the mobile base, equipped with wheels, can roll ensuring rectilinear motion. Different mechanisms were studied to realize this type of locomotion method. One solution, S2, uses the friction between wheels and groove walls as driving force. In S2, it is simple to move orthogonally by coordinating the motion direction of the wheels, see Fig. 2b (left). A second solution, S3, is to use independent driving motors to propel and steer each wheel. To rotate the base the four wheels reorient at the same time rotating about a vertical axis with zero-turning radius, see Fig. 2b (right). This solution proves to be costly given the necessity of one motor per wheel; furthermore it is difficult to achieve a design compact enough to fulfill the size constraints of the base.

3.3. Tracks

For the proposed mechanism (S4) tracks with conical pins are used to generate thrust and move the agent on the bench. The pins can be rigid or compliant. If compliant pins are used, the accurate positioning can be obtained with additional pins sliding vertically in the bench during the docking cycle, as shown in Fig. 2c.

3.4. Direct rolling

This method is conceived by having the base rolling directly on the bench to the target location. The mechanism S5 implements this method by having a frame with two rollers, capable to rotate about a vertical axis, a separate outer-frame with four pins is used to dock rigidly to the bench. When the base is in motion, the frame with the rollers is pulled down assuring contact between rollers and bench and preventing contact between pins and bench. Once in the desired location, the roller frame is lifted up, by doing so the pins are inserted in the bench docking with the necessary stiffness. At this moment, there is no contact between rollers and bench and the roller frame is free to rotate in case a change in direction for the next repositioning is in order, see Fig. 3.

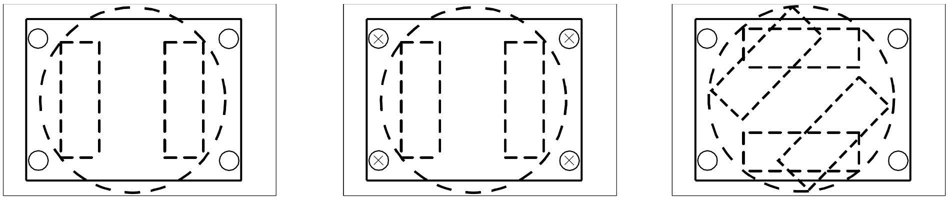


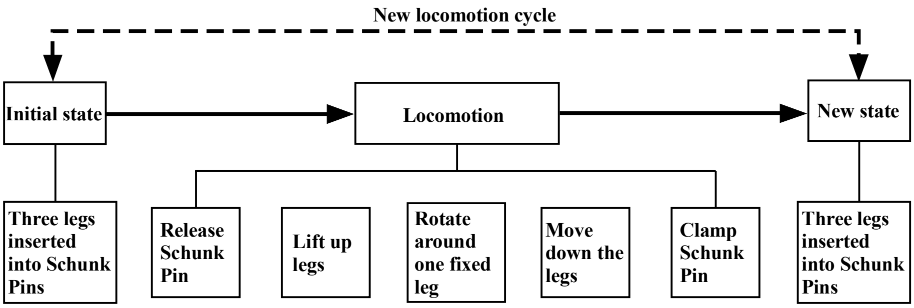
Fig. 3. Direct rolling: S5 mechanism change direction procedure.

3.5. Swing locomotion

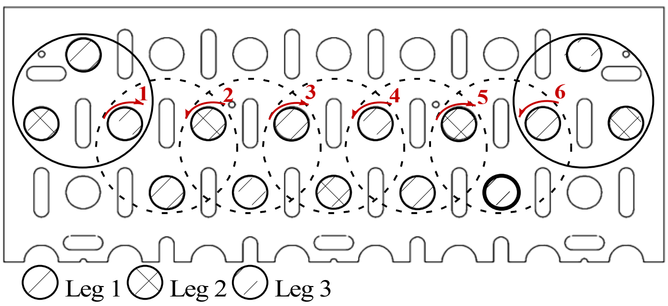
The swing locomotion method S6, is the one finally implemented in the prototype of the SwarmItFIX mobile base. The mobile base is equipped with pins, able to move and rotate about its axis. The pins are alternatively inserted in the workbench. The base rotates at an angle about the inserted pin (the pivot) and stops with the other pins facing exactly free workbench clamping devices. Then, one of the free pins slides in and the one previously acting as a pivot slides out. The presence of at least one inserted pin at all times guarantees equilibrium during locomotion. To assure the required stiffness, during manufacturing operations all pins are locked in the bench increasing the stiffness.

Fig. 4a shows a sequence of steps and

Fig. 4b shows the locomotion method flow chart.



a)

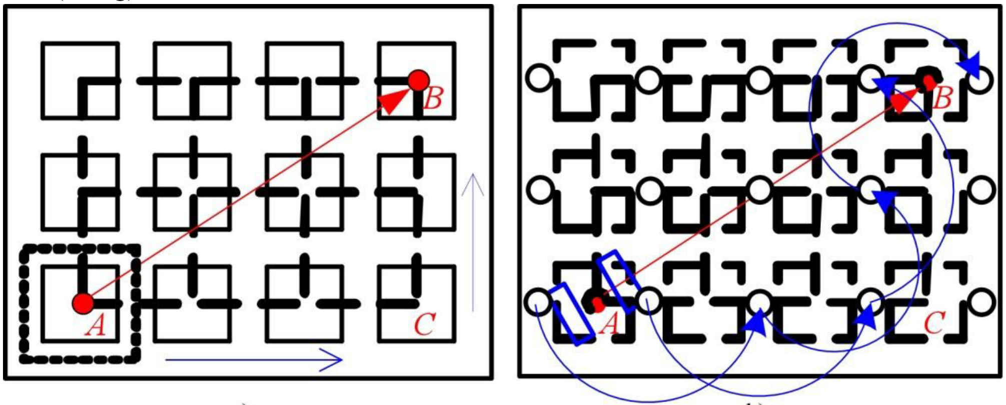


b)

Fig. 4. Swing locomotion: a) S6 repositioning sequence; b) flow chart of the S6 locomotion method

4. Comparison of Locomotion Methods

Three indexes are selected in order to obtain a fair comparison of the alternative locomotion methods presented in the previous section: forward velocity (V), positioning accuracy (A), and stiffness (k). In order to realize a consistent comparison between the locomotion methods some prerequisites have to be established: (1) similar bench size for all methods, with a maximum mobile base diameter of 350mm and a maximum distance between bench columns of 230mm; (2) regardless the design and locomotion method the maximum weight of the agent is 150 kg; (3) The time considered for the changes of direction and for the translations of the pins is 0.1s; (4) considering the size of the base, the diameters of wheels and rollers is considered as 45mm; (5) the trajectories compared is the same for all locomotion methods, as shown in Fig. 5a for the linear-motion methods and Fig. 5b for the rotational (swing) methods.



a) b)

Fig. 5. Base trajectory for comparison: a) Linear locomotion methods, b) Rotational locomotion methods

4.1. Forward velocity

Starting with the diagonal trajectory shown in Fig. 5a, the motor speed comparison is realized for the linear locomotion methods. The displacement of the agent is:

$$l_{AB}^2\sqrt{l_{AC}^2 + l_{CB}^2} \quad (1)$$

Where $l_{AC} = 690mm$ and $l_{CB} = 460mm$ and then $l_{AB} = 830mm$. As average target velocity we consider $v_r = 700\ mm/s$. Hence, the trajectory has to be completed in:

$$t_r = \frac{l_{AB}}{v_r} = 1.185s \quad (2)$$

Following the steps in the locomotion methods we obtain that the distance covered in the case of rectilinear locomotion methods S1 to S3:

$$l_j = l_{AC} + l_{CB} = 1150mm \quad (3)$$

Given that the mechanisms for linear locomotion methods permit only cartesian movements, at least one change in direction is needed. The real time spent moving forward for S2-4 is t1 and for S1 is t2 both reported in eq. 4

$$t_1 = t_r - 0.1 = 1.085, \;\; t_2 = \frac{t_r - 0.1}{2} = 0.543 \quad (4)$$

The rotational speeds of the driving motors for S1 and S2-4 respectively, are obtained and reported in eq. 5, 6

$$w_1 = \frac{1150}{1.085}/22.5 \times \frac{60}{2\pi} = 450\, r/min \quad (5)$$

$$w_2 = \frac{1150}{0.543}/22.5 \times \frac{60}{2\pi} = 900\, r/min \quad (6)$$

The real sequence of motions in the case of the locomotion methods S5 and S6 is shown in Fig. 5b. The total angular displacement of S6 is:

$$\alpha_{AB} = \pi + \pi + \frac{3\pi}{2} + \pi + \frac{3\pi}{2} = 6\pi \quad (7)$$

In a similar way the rotational speeds for the locomotion methods S5 and S6 are calculated and the results are: $w_5 = 358\ r/min$ for S5; and $w_6 = 1651\ r/min$ for S6

4.2. Accuracy

Errors originating during the displacement along the bench are considered. The position error of S1 comes from the gear meshing error while that of S2 and S3 is due to the slippage during acceleration and deceleration. Compared to S2-3, the solutions S5 and S6 have an additional rotational error occurring in the process of changing direction. The linear positioning error for S1, S4 and S6 is nearly zero.

4.3. Stiffness

The stiffness is a very critical factor to perform manufacturing operations as it affects directly the surface quality. The docking mechanism itself, as well as the number of joints between it and the frame of the parallel robot, has a determining influence on the stiffness. Fig. 6 represents the contact forces between the pin and docking whole of the workbench.

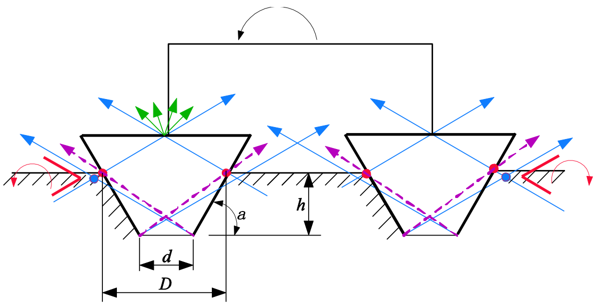


Fig. 6. Pin stiffness analysis

The highest stiffness is obtained satisfying the following: $\tan\alpha \le \frac{2h}{D-d}$ and $\frac{\pi}{4} < \alpha \frac{\pi}{2}$

In the case S6, only one pin is inserted in the bench during the repositioning and the offset of the center of gravity has to be taken into account. This moment is calculated as M _ Gr = 257.3Nm.

The solution S6 is selected because the agent is connected mechanically to the bench during the whole repositioning cycle with no risk to accumulate errors which would be difficult to recover during the docking phase. Moreover, in this way it is possible to feed electric power to the agent continuously and thus avoid a cable connection to ground which would create problems when a swarm of multiple agents is in operation. A good compromise is obtained regarding the achievable velocity of repositioning, which is comparable to the one with rollers or wheels on short distances and along diagonal trajectories. The locomotion principle is robust to the typical presence of large quantities of cutting chips on the bench.

5. Mobile base design

The mobile base or platform must interface with the bench and the PM allowing the supply of air and power. The accurate positioning of the end effector is obtained by a combination of base locomotion and locking, and PM motion, the former providing discrete macro-positioning and the latter ensuring a fine positioning. Using the swing locomotion method, the mobile base's final design integrates three foot-pins, able to rotate and move along its axis. The pins are inserted alternatively in the work bench; the base rotates at 60 degrees increments about the single inserted pin and stops with the remaining two pins facing exactly free workbench clamping devices. Then, one of the free pins slides out and locks to the bench, while the previous pivoting pin slides in. The final design is shown in Fig. 7.

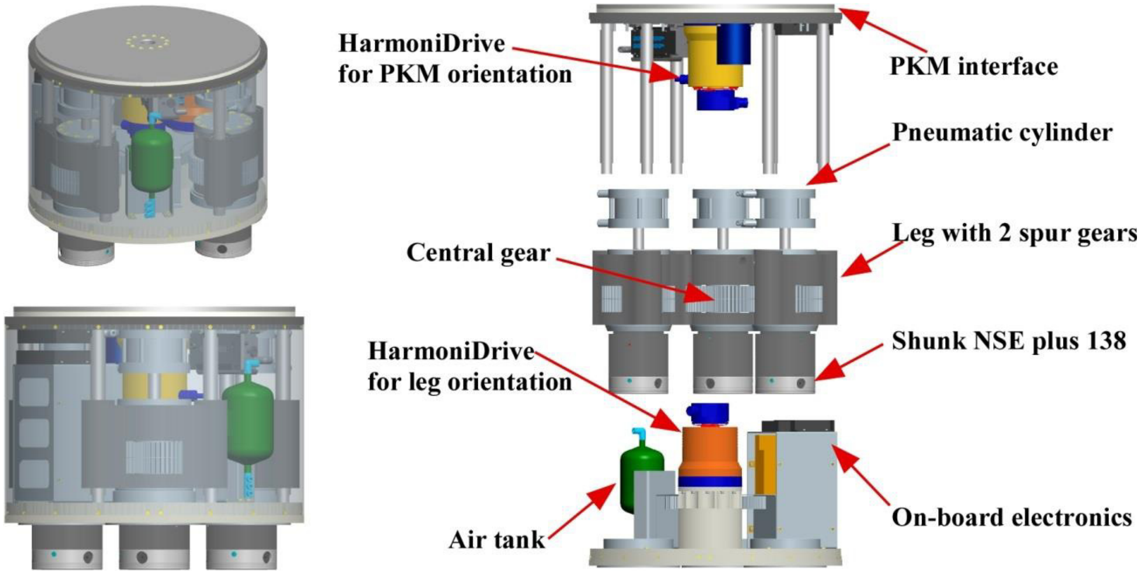


Fig. 7. Exploded view of the SwarmItFIX mobile base final design.

Two Harmonic Drives are located in the mobile base, one driving the rotation of the PM module and one driving the rotations of the three feet. The latter is achieved through a special gear transmission comprising two spur gears in each foot that permits the three feet, regardless of their position, to rotate together maintaining constant orientation with respect to the bench. This is necessary because the locking devices, embedded in the foot-pins, are intended to transmit both compressed air and electric power to the whole agent from the work bench. Each foot comprises a pneumatic cylinder for the vertical motion. Moreover, some electronic components are also integrated in the base: a Festo valve block, a DC-DC converter, a capacitor, and two Maxon position controllers for the harmonic drives. An air tank located in the base is filled constantly through the locked foot-pin assuring that air supply is always present throughout each repositioning cycle.

Fig. 8a illustrates the foot assembly, with cross-sections. The section in Fig. 8b shows that the translational motion of the leg is limited by a conic part fixed in the bottom part. When the pin reaches the desired extended position the conic ring mounted on the foot will be pressed into the conic part at the bottom of the base. Also shown, in Fig. 8c-d, are cross sections of the air distributer (in orange). Three channels are available: one for the Schunk module activation, one for cleaning the conic surfaces, and one to pass the compressed air coming in through the Schunk modules to the tank and agent.

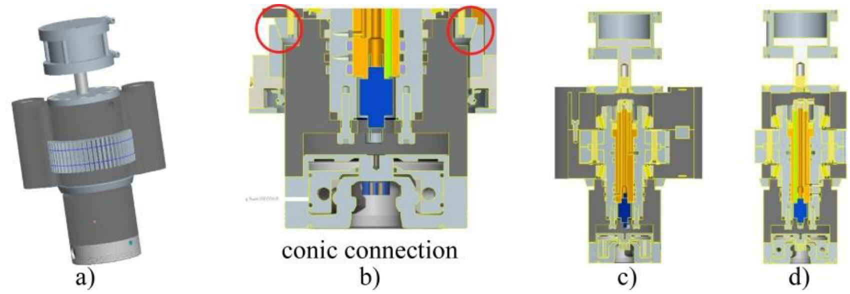


Fig. 8. Foot-pin assembly detailed. a) complete assembly, b, c, d) different cross section views of the foot pin assembly.

The mobile base was designed in parallel with the work bench in order to achieve an easy integration and ensure the transmission of power and air through the modified Schunk clamping devices. Fig. 9 shows the modified clamps with integrated electric connectors specially developed for the system. The bench is equipped with 52 columns embedding the male Schunk pin, an electrical connector, and an air-supply valve.

In Fig. 10, three feet are docked in the bench; this is the required configuration during the machining of workpiece. Before the docking clamps lock to the pins, the contact area is cleaned up by an air jet. For this purpose, air channels are located inside the foot. Two holes in the female electrical connector blow the air towards the contact surface.

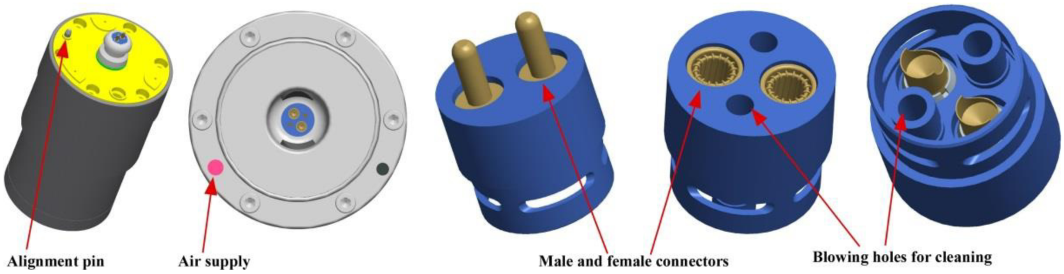


Fig. 9. Electric and air supply connectors embedded in the Schunk modified modules.

Also visible are the male electrical connector embedded in the male pin. Each of the pins located in the bench has a connector, and since at least one leg is always docked to the bench the electric power is never lost. The air supply is taken from the bench: when a Schunk locker is clamped, the air key is open by the contact and air flow through the leg keeping the tank full.

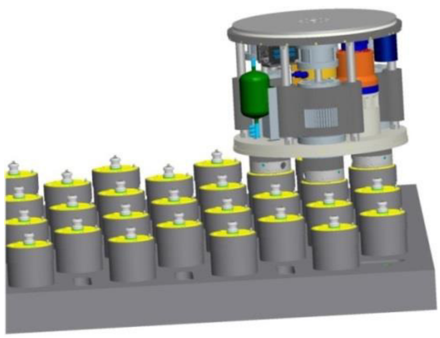


Fig. 10. Mobile base docked to the bench.

6. Conclusions

The mobile base developed within the SwarmItFIX project is capable of moving on the work bench with a repositioning time of 4 seconds. This is ensured by the sufficiently high speeds provided by the HD motors and the pneumatic cylinders. Each of the latter has a stroke of 45 mm and is capable to complete the actuation of a foot-pin in less than 1 second. Two harmonic drives were used, one for rotation of the whole base about one leg, as required by the novel swing locomotion method, and one for rotating the PM.

The mobile robot base is capable of two types of operation: either wire-free in which air and power are supplied from the bench; or using umbilical cords. This provides the capability to also operate the agent away from the bench, e.g. for reconfiguration or maintenance activities. The Schunk pins and lockers were modified in order to embed electrical and air connectors, allowing the transmission of electrical power to the whole agent from the bench as well as the supply of air to the onboard tank.

A physical prototype demonstrator of the complete fixture system was manufactured and installed in Piaggio Aero Industries premises in Finale Ligure, Italy [2]. A first testing period was conducted during the project and further tests are ongoing.

Acknowledgements

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